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RESEARCH MEMORANDUM

PRELIMINARY RESULTS FROM FREE-JET TESTS OF A 48-INCH-DIAMETER RAM-JET COMBUSTOR WITH AN ANNULAR-PILOTED BAFFLE-TYPE FLAMEHOLDER

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NATIONAL ADVISORY COMMITTEE FOR AERONAUTICS

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SUMMARY

A ram-jet engine with an experimental 48-inch-diameter combustor was investigated in a free-jet facility. The combustor design comprised a large-volume annular pilot region and an array of sloping baffle- or gutter-type flameholders. The combustor was intended to operate at a fuel-air ratio of about 0.037. To promote combustion efficiency at such low fuel-air ratios, a divided-flow system was employed which bypassed a portion of the engine air around the combustion region.

Three combustor lengths, three lengths of the shroud which separated the bypass air from the burning stream, and four fuel-distribution systems were investigated over a range of fuel-air ratios from 0.025 to 0.055 and a range of engine air flows from 40 to 110 pounds per second (combustor-outlet total pressures from 500 to 1800 lb/sq ft abs).

The highest efficiencies were obtained with a combustor length of 78 inches and a shroud length of 6 inches. At the lowest air flow, with combustor pressures of about 700 pounds per square foot absolute, a maximum efficiency of about 93 percent was obtained. The efficiency increased with combustor length, a typical increase being from 88 to 95 percent as the length increased from 60 to 96 inches. The length of the shroud separating the bypass air from the burning stream affected not only the efficiency level, but also the fuel-air ratio at which the maximum efficiency occurred. In general, a longer shroud caused the maximum efficiency to occur at lower fuel-air ratios. Highest efficiencies usually resulted from the use of a fuel-injection system giving a uniform fuel profile. The efficiency at low fuel-air ratios could be considerably improved by the use of a radially nonuniform fuel profile which concentrated the fuel towards the outermost portion of the burning stream.

The total-pressure ratio across the combustor was about 0.86 at the design point.

An electrical-spark ignition system proved capable of starting the engine at all conditions investigated and ignition was found not to depend on the use of pilot fuel.

INTRODUCTION

The performance of an experimental 48-inch-diameter combustor in a ram-jet engine was investigated in a free-jet facility at the NACA Lewis laboratory. This investigation was a part of a continuing program aimed at determining combustor configurations and engine geometries capable of delivering high performance at conditions simulating those experienced by a long-range ram-jet-powered vehicle.

The fixed-area exhaust nozzle was sized to accommodate a combustor operating with 100 percent efficiency at an over-all fuel-air ratio of 0.034. The combustor used was a modification of one previously investigated in a direct-connect system (ref. 1). It employed a large-volume annular pilot in conjunction with an array of sloping baffle- or gutter-type flameholders. In order to operate efficiently at fuel-air ratios considerably less than stoichiometric, a divided-flow system was used in which a portion of the engine air was bypassed around the combustion region. This bypass air was permitted to mix with the main stream at a station downstream of the flame-holding elements.

Combustor performance was evaluated for three combustor lengths, 96, 78, and 60 inches, and four fuel-distribution systems. The point at which the bypass air was permitted to rejoin the main stream was also varied. The air flow through the engine was varied from 40 to 110 pounds per second to give a range of combustor outlet pressures from 500 to 1800 pounds per square foot absolute. The range of fuel-air ratios investigated was between 0.025 and 0.055. The upper limit was usually established by the critical pressure recovery of the supersonic diffuser.

The results of this investigation are presented both in tabular and in graphic form. The combustion efficiencies given were calculated from the effective area of the exhaust nozzle, the mass flow of air through the engine, the total pressure of the gas entering the exhaust nozzle, and the fuel flow. They represent the ratio of the fuel flow ideally required to give the observed total pressure at the exhaust nozzle to the fuel flow actually used.

APPARATUS

Facility

A 48-inch-diameter ram-jet engine was tested in a free-jet facility. The starting and performance characteristics of the free-jet facility have been previously reported (ref. 2). A sketch of the experimental configuration is shown in figure 1. An asymmetrical supersonic diffuser, which was connected to the combustor by a simple conical section of 30° half-angle, had an outlet-velocity profile which was circumferentially nonuniform. To improve the profile and to avoid flow separation, a half-screen was installed in the high-velocity portion of the diffuser outlet. This screen comprised a square array of 1/4-inch rods and blocked 20 percent of the (half) area.

Combustor

The combustor shell was constructed of three cylindrical sections 42, 36, and 18 inches in length to permit variation of combustor length. These sections, as well as the exhaust nozzle were water-cooled. The convergent-divergent exhaust nozzle had a 54.6 percent open area; the half-angle of the convergent section was 25°; the half-angle of the divergent section was 12°. A motor-operated clam-shell (not shown) was attached to the exhaust nozzle to facilitate the obtaining of cold-flow drag data. The cross section of the combustor is shown in figure 1; a cutaway view is given by figure 2.

The flameholder configuration, which resembled one previously tested in a direct-connect system (ref. 1), was composed of an annular pilot connected to sloping V-gutter flameholders. The combustor extended forward to the beginning of the 30° cone section, and divided the air into two parts. From 20 to 30 percent of the air was routed around the combustion region and was separated from the burning stream by a cylindrical shroud. The length of this shroud was varied during the investigation.

Approximately 0.1 percent of the total air flow was bled from the bypass air stream into the pilot annulus. Fuel for the pilot region was supplied by four evenly spaced bars (figs. 1 and 2). Twin orifices in each bar sprayed fuel in the circumferential direction.

Fuel was injected normal to the main air stream by means of simple orifices in sixteen 1/2-inch-diameter radial tubes equally spaced circumferentially, and supplied from a common external manifold. Three such systems, differing only in size and location of fuel orifices, were incorporated in a single installation to facilitate the study of fuel profile effects. The corresponding tubes from each fuel system were combined into single fuel bars. Figures 1 and 2 show a typical fuel bar

installed in the combustor. The circumferential locations of fuel bars, as well as the four basic fuel-distribution profiles investigated are shown in figure 3.

The fuel used throughout the investigation was MIL-5624-B, grade JP-5, with a heating value of 18,625 Btu per pound and a hydrogen-carbon ratio of 0.159.

Ignition was achieved through the use of two surface-discharge spark plugs located in the pilot annulus. A separate power system of the condenser-discharge type was used to supply each plug. 3576

Instrumentation

The air flow through the engine was determined from the effective capture area of the supersonic diffuser and the total pressure and temperature upstream of the free-jet nozzle. Cold-flow tests with a small exhaust nozzle were used to determine the effective capture area of the diffuser. Total pressures were measured in the engine at stations 3 and 6 (see fig. 1). At station 3, the diffuser outlet, the 48 total-pressure tubes were located on six radial bars and were spaced radially in eight equal areas. At station 6, the combustor outlet, the 33 tubes were located on four radial bars and spaced radially in eight equal areas with the odd tube being located in the center of the total area. These tubes were all connected to mercury manometers, the wells of which were in turn connected to a manifold kept within 1/2 pound per square foot of absolute zero by a vacuum pump.

The air temperature entering the engine was measured by an 18-point thermocouple array located upstream of the free-jet nozzle. Total temperature was assumed to be conserved through the diffuser. The temperature of the gas near the wall at the entrance to the exhaust nozzle was measured by four thermocouples located $1\frac{1}{2}$ inches from the wall and equally spaced about the circumference.

The quantity of bypass air was determined from measurements of total and static pressure in the bypass channel.

Fuel-flow measurements were obtained from the pressure drop across sharp-edged orifices. These orifices were calibrated by comparison with standard rotameters. Separate measurement of the fuel flowing to each of the main fuel manifolds was made by means of a positive displacement electronic flowmeter.

The flow of cooling water to the engine was metered through a flat-plate orifice. The temperature rise of the coolant was determined from two thermocouples located upstream and downstream.

The mercury manometers measuring pressures at stations 3 and 6, as well as manometers connected to read static pressures at various points within the engine, were recorded photographically. The various temperatures were recorded by a self-balancing potentiometer.

In addition, the appearance of the unit in operation was observed by means of a periscope located downstream of the engine, which afforded a view of the combustion region through the exhaust nozzle.

PROCEDURE

Five combinations of combustor and shroud lengths were studied with various air-flow rates and temperatures as shown in the following table:

Combustor length, L_c, in.	Shroud length, L_s, in.	Engine air flow, W_e, lb/sec Air temperature, T_{in}, °F				
		$W_e = 40$ $T_{in} = 530$	$W_e = 60$ $T_{in} = 530$	$W_e = 80$ $T_{in} = 530$	$W_e = 80$ $T_{in} = 400$	$W_e = 110$ $T_{in} = 400$
96	70		x	x	x	x
96	29		x	x	x	x
78	6	x	x	x		
60	29		x	x	x	x
60	6	x	x	x		

At each condition, data were taken over a range of fuel-air ratios from about 0.025 to 0.055, with the upper limit being dependent upon combustion efficiency. At 100 percent combustion efficiency, a fuel-air ratio of less than 0.050 was sufficient to cause the diffuser to go subcritical. Limits on the facility prevented any data being taken with subcritical diffuser operation. The approximate combustor-outlet pressures associated with each air-flow condition are as follows:

Air-flow condition		Range of combustor-outlet total pressure, P_6, lb/sq ft abs	Combustor-outlet total pressure at design point $(f/a_{id} = 0.034)$
W_e, lb/sec	T_{in}, °F		
40	530	500-700	650
60	530	800-1050	980
80	530	1100-1400	1300
80	400	1100-1400	1280
110	400	1500-1800	1760

The four fuel-distribution profiles shown in figure 3 were used. Most of the data were taken with the more uniform profile A. In the later phases of the program, profiles C and D were used in combination to provide either a plane profile equivalent to that of A or to give high fuel concentrations either in the center or at the outer edge of the burning stream. The amount of fuel supplied to the pilot was varied from zero to a value giving an over-all fuel-air ratio of 8 percent of stoichiometric. Most of the data, however, were taken with a pilot fuel flow giving 2.5 percent of the stoichiometric fuel-air ratio.

No effort was made to control the flow rate of the bypass air. The quantity varied throughout the tests, being a function of both shroud length and of the fuel-air ratio of the engine. In general, the bypass air was less than 20 percent of the total air for cold flow, and increased with increasing fuel-air ratio up to as much as 30 percent.

Ignition tests were conducted in the following manner. First, the supersonic flow through the free-jet was established. The air temperature was then raised to the required value, and the mass flow through the engine adjusted. Pilot and/or main fuel was turned on; when main fuel was used, a quantity giving an over-all fuel-air ratio of 0.035 was most frequently employed. The electric spark was turned on and the results noted. Whether the spark preceded or followed the introduction of the fuel was found to be unimportant. Data for the preignition engine pressures were obtained from the cold-flow tests, wherein no fuel was injected.

RESULTS

The engine performance and ignition data obtained are summarized in tables I and II. The performance of the five combinations of combustor length and shroud length is presented in table I. Figures 4 to 9 present the same data in graphic form. Figure 4 shows the combustion efficiency, combustor-outlet total pressure, inlet Mach number, and combustor pressure ratio as functions of ideal fuel-air ratio for an air-flow rate of 60 pounds per second. Fuel profile A was used throughout. As can be seen by the efficiency curves, a decrease in combustor length resulted in a decrease in efficiency level without any change in the shape of the efficiency curve. The peak efficiency with fixed shroud length was decreased from 95 to 88 percent when the combustor length was reduced from 96 to 60 inches. Variation in shroud length, on the other hand, resulted in a drastic change in the shape of the efficiency curve. For the long shroud (70 in.) the peak efficiency occurred at an ideal fuel-air ratio less than 0.028. For the 29-inch shroud, a very flat peak in the region between 0.030 and 0.042 was found. For the 6-inch shroud, the maximum efficiency resulted from an ideal fuel-air ratio of about 0.045 which corresponds closely to a fuel-air ratio yielding a stoichiometric mixture in the burning stream. Similar results were obtained at an air flow of

80 pounds per second at inlet temperatures of 530° and 400° F, and an air flow of 110 pounds per second at an inlet temperature of 400° F. These results are presented in figures 5 to 7.

The configuration yielding the highest peak efficiency was the 78-inch combustor with the short 6-inch shroud. No data were obtained for the combination of 96-inch combustor length and 6-inch shroud length, which might logically be expected to exhibit a somewhat better performance than those investigated. For the range of combustor pressures between 950 and 1800 pounds per square foot absolute, little change in peak efficiency level with pressure was apparent, as shown by figures 4 to 7. For example, the 29-inch shroud in the 96-inch combustor gave a peak efficiency of about 95 percent for combustor pressures within this range. The configuration giving the highest efficiency was also investigated at an air flow of 40 pounds per second (combustor outlet total pressures from 500 to 700 psfa). The performance of this configuration at three pressure levels is presented in figure 8. At the two higher pressure levels, the peak efficiency of about 98 percent occurred at an actual fuel-air ratio of about 0.045. At the low-pressure level, the peak efficiency again occurred at an actual fuel-air ratio of about 0.045, but was reduced to about 93 percent.

The effect of fuel profile on combustion efficiency is shown in figure 9. Figures 9(a) and (b) represent data taken at an engine air flow of 60 pounds per second. The performance of the combustor with fuel profile A is used as a standard with which to compare the performance with profiles B and C. Since the combustor and shroud lengths are not the same for the two sets of curves, they should not be compared directly. Fuel profile B yielded a lower efficiency at all fuel flows than did profile A. Profile C, on the other hand, gave a considerable increase in combustion efficiency at the lower fuel-air ratios, and decreased at the higher. The same general relation between profile A and C is seen in figure 9(c) for an air flow of 40 pounds per second. At an actual fuel-air ratio of 0.035, the effect of proportioning the fuel between profiles C and D is shown by figure 9(d). When the fuel flow is divided equally between C and D, a profile equivalent to profile A should result. The efficiency fell off as the amount of fuel to profile D was increased.

The total-pressure ratio across the combustor varied little between the five combinations of combustor and shroud length, and ranged from 0.83 to 0.89 with variation in fuel-air ratio. At the design point, the total-pressure ratio was about 0.86.

As shown by table II, electric ignition of the engine was successful over a wide range of operating conditions. Static pressures in the pilot annulus were as low as 260 pounds per square foot absolute immediately prior to ignition. The two instances in which ignition was not obtained were at the two lowest pressures. Visual observation through the periscope indicated that the pilot fuel might be quenching the spark for these tests; thereupon, the pilot fuel was turned off and successful starts at similar conditions were immediately obtained.

The distribution of static pressures in the main air stream in the region upstream of the pilot is shown for a typical starting condition on figure 10. The flow seems to be supersonic in the upstream region, a transition to subsonic occurring before the slots admitting air to the pilot are reached.

CONCLUDING REMARKS

The performance of the experimental 48-inch-diameter ram-jet combustor tested in a free-jet facility was as follows:

The highest combustion efficiencies were obtained with a 78-inch combustor and a 6-inch bypass air shroud. These efficiencies occurred at a fuel-air ratio of about 0.045, which yields a stoichiometric mixture in the burning stream. At the lowest combustor pressure, about 700 pounds per square foot absolute, efficiencies of about 93 percent were attained. The combustion efficiency increased with combustor length, a typical increase being from 88 to 95 percent as the length increased from 60 to 96 inches. The length of the shroud separating bypass air from the main stream affected not only the maximum efficiency, but also the fuel-air ratio at which the maximum efficiency occurred. In general, a longer shroud caused the efficiency peak to occur at lower fuel-air ratios.

The highest efficiencies were obtained with a fuel-injection system giving the more uniform fuel profile, while efficiency gains could be obtained at low fuel-air ratios by using a radially nonuniform fuel profile.

The total-pressure ratio across the combustor ranged from 0.83 to 0.89 with variation in fuel-air ratio, being about 0.86 at the design point.

An electric spark ignition system provided satisfactory ignition at all air-flow conditions tested. The static pressures in the ignition region were as low as 260 pounds per square foot absolute immediately prior to ignition. The separate fuel supply to the pilot was not found to aid ignition; on at least one occasion ignition was possible only with the pilot fuel turned off.

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APPENDIX

SYMBOLS AND CALCULATIONS

The following symbols are used in this report:

f/a_{act} actual fuel-air ratio in engine, (lb fuel)(sec)/(lb air)(sec)

f/a_{id} ideal fuel-air ratio (fuel-air ratio necessary to cause observed engine-outlet total pressure and observed heat loss)

L_c length of combustor (cylindrical section only), in.

L_s length of shroud, in.

M_{in} Mach number at engine inlet, based on inlet total pressure and temperature, and maximum (48-in.) diameter

P_3 total pressure at engine station 3 (diffuser outlet), psfa

P_6 total pressure at engine station 6 (engine outlet), psfa

p_p static pressure in pilot annulus, psfa

T_{in} total temperature at engine inlet, assumed to be same as at inlet to free-jet nozzle, $^{\circ}F$

T_x indicated temperature at exhaust-nozzle inlet, $1\frac{1}{2}$ in. from wall of engine, $^{\circ}F$

W_b ratio of air flow through bypass to total flow through engine

W_e air flow through engine, lb/sec

η_c combustion efficiency, percent

Combustion efficiency as used herein is defined as ratio of fuel ideally required to give observed exhaust pressure and heat rejection to that actually supplied to engine, or $\eta_c = \dfrac{f/a_{id}}{f/a_{act}}$.

From tables of theoretical temperature rise for combustion as a function of fuel-air ratio and initial temperature, charts were prepared showing ideal fuel-air ratio as a function of engine-inlet temperature,

air-flow rate, and engine-outlet total pressure. In preparing these charts an exhaust-nozzle discharge coefficient of 0.99 was assumed, which results in an effective area of 54.1 percent. This value for the flow coefficient was obtained from reference 3 for a similar nozzle. To the ideal fuel-air ratio necessary to account for the engine-outlet total pressure, a small correction was added to supply the heat that was added to the cooling water. In making this correction, it was assumed that the heat added to the cooling water during cold-flow tests came in equal parts from the inside and from the outside of the engine. Thus the total amount of heat added to the coolant during burning tests was reduced by one-half the amount added in cold-flow tests before making the heat-loss correction. 3576

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TABLE I. - PERFORMANCE DATA FOR EXPERIMENTAL COMBUSTOR IN A 48-INCH-DIAMETER RAM-JET ENGINE

(a) Combustor length, 96 inches; shroud length, 70 inches

Engine air flow, W_e, lb/sec	Inlet temperature, T_{in}, °F	Bypass air, W_b, percent	Combustor-inlet Mach number, M_{in}	Pilot fuel, percent stoichiometric	Main fuel distribution, percent, to profiles -				Gas temperature near wall of exhaust nozzle, T_x, °F	Engine-outlet pressure, P_6, lb/sq ft abs	Pressure ratio across combustor, P_6/P_3	Fuel-air ratio		Combustion efficiency, η_c, percent
					A	B	C	D				Actual, f/a_{act}	Ideal, f/a_{id}	
59.5	528	17	0.169	----	--	--	--	--	420	831	0.825	---	---	--
59.4	533	17	.159	---	--	--	--	--	427	927	.862	---	---	--
59.2	536	20	.149	---	--	--	--	--	438	999	.875	---	---	--
59.4	530	20	.144	---	--	--	--	--	432	1068	.901	---	---	--
59.3	527	27	.160	2.3	100	--	--	--	692	903	.847	0.0300	0.0277	92.3
59.1	532	28	.154	2.3	100	--	--	--	713	945	.854	.0362	.0322	89.0
59.0	532	30	.149	2.4	100	--	--	--	695	975	.858	.0409	.0357	87.3
59.0	530	31	.149	2.4	100	--	--	--	662	985	.868	.0409	.0367	89.5
59.0	531	32	.147	2.4	100	--	--	--	673	1005	.871	.0462	.0389	84.0
59.0	531	32	.145	2.3	100	--	--	--	690	1024	.878	.0513	.0412	80.3
58.9	531	27	.146	2.3	--	100	--	--	738	1024	.880	.0512	.0414	80.9
59.0	531	32	.147	2.4	--	100	--	--	718	1004	.870	.0467	.0389	83.1
59.0	532	30	.150	2.3	--	100	--	--	762	981	.867	.0415	.0361	87.0
59.0	529	28	.154	2.4	--	100	--	--	740	940	.855	.0362	.0319	88.1
59.3	523	25	.162	2.4	--	100	--	--	613	872	.834	.0299	.0252	84.3
59.0	533	31	.149	2.4	74	26	--	--	675	984	.864	.0410	.0364	88.8
59.3	522	26	.159	2.4	61	39	--	--	660	899	.843	.0301	.0276	91.4
59.1	523	28	.153	2.4	59	41	--	--	705	951	.861	.0360	.0330	91.7
59.5	523	31	.151	2.4	60	40	--	--	680	986	.868	.0405	.0359	88.6
59.1	531	30	.147	2.4	59	41	--	--	712	1010	.873	.0460	.0393	85.4
59.0	531	31	.150	2.4	21	79	--	--	700	976	.863	.0410	.0356	86.8
59.3	528	30	.150	1.3	100	--	--	--	673	986	.870	.0404	.0365	90.4
59.1	533	31	.150	5.4	100	--	--	--	655	986	.871	.0413	.0365	88.4
59.2	530	30	.151	8.2	100	--	--	--	652	967	.861	.0404	.0343	84.9
78.9	529	27	.158	2.5	100	--	--	--	682	1219	.852	.0312	.0291	93.3
78.6	534	25	.154	2.5	100	--	--	--	702	1268	.863	.0362	.0327	90.3
78.8	531	31	.150	2.5	100	--	--	--	675	1310	.867	.0408	.0361	88.5
78.9	533	32	.148	2.6	100	--	--	--	660	1346	.875	.0458	.0390	85.2
79.0	531	32	.146	2.6	100	--	--	--	712	1373	.880	.0510	.0414	81.2
79.2	399	28	.154	2.6	100	--	--	--	538	1188	.863	.0311	.0281	90.4
79.3	402	32	.149	2.6	100	--	--	--	552	1248	.874	.0359	.0323	90.0
78.8	404	31	.146	2.6	100	--	--	--	572	1287	.886	.0410	.0358	87.3
79.4	397	31	.143	2.5	100	--	--	--	600	1332	.899	.0458	.0387	84.5
79.3	405	31	.143	2.5	100	--	--	--	587	1343	.901	.0505	.0397	78.6
108.1	401	28	.155	2.7	100	--	--	--	592	1630	.875	.0322	.0285	88.6
107.9	404	31	.150	2.7	100	--	--	--	557	1698	.878	.0361	.0322	89.2
107.6	406	30	.146	2.6	100	--	--	--	597	1756	.887	.0411	.0356	86.6
108.5	402	30	.144	2.7	100	--	--	--	637	1813	.900	.0458	.0381	83.2

TABLE I. - Continued. PERFORMANCE DATA FOR EXPERIMENTAL COMBUSTOR IN A 48-INCH-DIAMETER RAM-JET ENGINE

(b) Combustor length, 96 inches; shroud length, 29 inches

Engine air flow, W_e, lb/sec	Inlet temperature, T_{in}, °F	Bypass air, W_b, percent	Combustor-inlet Mach number, M_{in}	Pilot fuel, percent stoichiometric	Main fuel distribution, percent, to profiles - A	B	C	D	Gas temperature near wall of exhaust nozzle, T_x, °F	Engine-outlet pressure, P_6, lb/sq ft abs	Pressure ratio across combustor, P_6/P_3	Fuel-air ratio: Actual, f/a_{act}	Ideal, f/a_{id}	Combustion efficiency, η_c, percent
59.4	532	- -	0.166	- -	- -	- -	- -	- -	435	868	0.844	- - -	- - -	- -
59.5	534	19	.161	- -	- -	- -	- -	- -	437	916	.863	- - -	- - -	- -
59.6	533	18	.156	- -	- -	- -	- -	- -	438	967	.878	- - -	- - -	- -
59.5	530	21	.148	- -	- -	- -	- -	- -	433	1037	.899	- - -	- - -	- -
59.6	526	20	.144	- -	- -	- -	- -	- -	433	1074	.907	- - -	- - -	- -
59.2	530	21	.167	2.4	100	- -	- -	- -	1068	848	.831	0.0262	0.0225	85.9
59.5	526	24	.159	2.4	100	- -	- -	- -	1142	908	.846	.0302	.0281	93.1
59.5	526	27	.152	2.3	100	- -	- -	- -	1135	964	.858	.0353	.0335	94.9
58.9	535	29	.147	2.3	100	- -	- -	- -	1275	1005	.870	.0411	.0389	94.7
58.9	535	29	.146	2.6	100	- -	- -	- -	1300	1012	.873	.0416	.0396	95.2
59.1	532	27	.144	2.3	100	- -	- -	- -	1345	1043	.885	.0464	.0434	93.5
59.2	531	24	.142	2.3	100	- -	- -	- -	1273	1067	.891	.0513	.0463	90.3
59.2	531	22	.165	2.4	- -	100	- -	- -	1017	866	.839	.0303	.0247	81.5
59.4	528	25	.156	2.4	- -	100	- -	- -	1087	938	.859	.0357	.0312	87.4
59.5	526	28	.149	2.4	- -	100	- -	- -	1205	1000	.872	.0410	.0374	91.2
59.1	534	28	.149	2.4	- -	100	- -	- -	1213	994	.869	.0415	.0375	90.4
59.0	535	29	.146	2.4	- -	100	- -	- -	1315	1033	.885	.0465	.0426	91.6
59.1	534	28	.144	2.3	- -	100	- -	- -	1343	1054	.889	.0514	.0452	87.9
79.9	533	24	.159	2.5	100	- -	- -	- -	1190	1235	.853	.0308	.0290	94.2
79.9	538	27	.152	2.5	100	- -	- -	- -	1207	1306	.863	.0359	.0342	95.3
79.4	537	30	.148	2.6	100	- -	- -	- -	1300	1357	.875	.0408	.0392	96.1
79.4	535	28	.145	2.5	100	- -	- -	- -	1402	1397	.883	.0454	.0430	94.6
79.2	532	28	.142	2.5	100	- -	- -	- -	1382	1429	.893	.0505	.0465	92.1
79.5	406	26	.154	2.5	100	- -	- -	- -	1013	1195	.862	.0308	.0284	92.2
80.1	404	29	.147	2.5	100	- -	- -	- -	1195	1280	.877	.0354	.0337	95.2
80.4	397	28	.145	2.5	100	- -	- -	- -	1225	1311	.885	.0379	.0358	94.3
79.3	407	28	.142	2.5	100	- -	- -	- -	1387	1334	.891	.0407	.0389	95.5
79.8	396	26	.141	2.5	100	- -	- -	- -	1282	1370	.903	.0457	.0416	90.9
109.0	402	21	.168	2.7	100	- -	- -	- -	1043	1465	.842	.0261	.0196	75.1
109.3	402	26	.155	2.6	100	- -	- -	- -	1043	1638	.868	.0308	.0281	91.2
109.0	411	28	.148	2.7	100	- -	- -	- -	1207	1749	.879	.0358	.0339	94.7
108.9	401	26	.145	2.7	100	- -	- -	- -	1292	1781	.888	.0381	.0360	94.5
108.8	403	27	.144	2.6	100	- -	- -	- -	1468	1820	.896	.0406	.0382	94.1

TABLE I. - Continued. PERFORMANCE DATA FOR EXPERIMENTAL COMBUSTOR IN A 48-INCH-DIAMETER RAM-JET ENGINE

(c) Combustor length, 60 inches; shroud length, 29 inches

Engine air flow, W_e, lb/sec	Inlet temperature, T_{in}, °F	Bypass air, W_b, percent	Combustor-inlet Mach number, M_{in}	Pilot fuel, percent stoichiometric	Main fuel distribution, percent, to profiles - A	B	C	D	Gas temperature near wall of exhaust nozzle, T_x, °F	Engine-outlet pressure, P_6, lb/sq ft abs	Pressure ratio across combustor, P_6/P_3	Fuel-air ratio: Actual, f/a_{act}	Fuel-air ratio: Ideal, f/a_{id}	Combustion efficiency, η_c, percent
59.6	531	17	0.162	--	--	--	--	--	450	896	0.849	--	--	--
59.6	530	19	.150	--	--	--	--	--	450	1013	.887	--	--	--
59.3	532	20	.144	--	--	--	--	--	456	1074	.908	--	--	--
78.6	532	17	.161	--	--	--	--	--	460	1187	.854	--	--	--
79.3	529	18	.153	--	--	--	--	--	460	1320	.889	--	--	--
80.0	526	20	.146	--	--	--	--	--	460	1424	.907	--	--	--
109.0	405	17	.155	--	--	--	--	--	360	1675	.888	--	--	--
109.4	404	20	.150	--	--	--	--	--	358	1762	.897	--	--	--
109.3	403	21	.146	--	--	--	--	--	365	1819	.909	--	--	--
59.7	528	21	.164	2.5	100	--	--	--	953	873	.837	0.0297	0.0243	81.8
59.8	532	24	.157	2.3	100	--	--	--	911	941	.857	.0350	.0306	87.4
60.0	526	28	.151	2.5	100	--	--	--	1107	988	.867	.0400	.0351	87.8
59.6	530	29	.147	2.5	100	--	--	--	1103	1022	.875	.0454	.0393	86.6
59.5	532	28	.144	2.5	100	--	--	--	1223	1051	.884	.0508	.0430	84.6
59.6	530	28	.143	2.5	100	--	--	--	1259	1069	.891	.0557	.0453	81.3
79.7	528	22	.162	2.5	100	--	--	--	975	1184	.842	.0302	.0257	85.1
79.2	537	25	.155	2.5	100	--	--	--	1000	1263	.860	.0356	.0317	89.0
79.5	529	29	.150	2.4	100	--	--	--	1095	1328	.871	.0404	.0363	89.9
79.4	531	29	.146	2.5	100	--	--	--	1115	1374	.879	.0456	.0404	88.6
79.8	528	27	.144	2.4	100	--	--	--	1170	1408	.885	.0500	.0433	86.6
78.7	414	25	.159	2.6	100	--	--	--	815	1143	.858	.0308	.0252	81.8
79.7	406	28	.151	2.4	100	--	--	--	995	1230	.869	.0353	.0302	85.6
79.3	399	28	.145	2.5	100	--	--	--	985	1290	.882	.0406	.0350	86.2
78.3	400	28	.143	2.6	100	--	--	--	948	1319	.898	.0448	.0389	86.8
109.2	402	28	.160	2.4	100	--	--	--	828	1578	.861	.0304	.0249	81.7
109.6	403	26	.156	2.5	100	--	--	--	911	1636	.867	.0327	.0275	84.1
109.7	401	28	.151	2.5	100	--	--	--	935	1701	.875	.0352	.0306	86.9
109.7	403	29	.149	2.4	100	--	--	--	953	1746	.882	.0376	.0330	87.8
109.1	404	28	.146	2.4	100	--	--	--	1011	1775	.887	.0399	.0351	88.0

TABLE I. - Continued. PERFORMANCE DATA FOR EXPERIMENTAL COMBUSTOR IN A 48-INCH-DIAMETER RAM-JET ENGINE

(d) Combustor length, 60 inches; shroud length, 6 inches

Engine air flow, W_e, lb/sec	Inlet temperature, T_{in}, °F	Bypass air, W_b, percent	Combustor-inlet Mach number, M_{in}	Pilot fuel, percent stoichiometric	Main fuel distribution, percent, to profiles - A	B	C	D	Gas temperature near wall of exhaust nozzle, T_x, °F	Engine-outlet pressure, P_6, lb/sq ft abs	Pressure ratio across combustor, P_6/P_3	Fuel-air ratio: Actual, f/a_{act}	Ideal, f/a_{id}	Combustion efficiency, η_c, percent
39.4	543	17	0.168	--	--	--	--	--	393	580	0.855	---	---	--
39.4	541	16	.164	--	--	--	--	--	329	598	.862	---	---	--
39.4	544	19	.161	--	--	--	--	--	349	622	.877	---	---	--
39.4	545	20	.151	--	--	--	--	--	361	672	.889	---	---	--
39.4	550	22	.146	--	--	--	--	--	365	720	.920	---	---	--
59.6	532	18	.172	--	--	--	--	--	440	828	.829	---	---	--
59.9	526	16	.163	--	--	--	--	--	440	890	.846	---	---	--
60.1	523	20	.159	--	--	--	--	--	445	941	.871	---	---	--
59.8	525	20	.151	--	--	--	--	--	445	1004	.884	---	---	--
61.3	522	22	.145	--	--	--	--	--	440	1101	.910	---	---	--
40.1	525	23	.149	3.6	100	--	--	--	1600	664	.859	0.0408	0.0354	86.8
39.6	528	21	.159	0	--	--	100	--	1073	606	.846	.0300	.0283	94.3
39.5	530	22	.153	0	--	--	100	--	1061	632	.854	.0353	.0322	91.2
39.7	527	25	.149	0	--	--	100	--	1183	657	.859	.0402	.0355	88.3
39.7	526	25	.146	0	--	--	100	--	1413	680	.872	.0461	.0393	85.2
39.7	524	25	.145	0	--	--	100	--	1487	693	.881	.0507	.0419	82.6
39.7	525	22	.144	0	--	--	100	--	1525	699	.885	.0559	.0432	77.3
39.6	530	22	.154	0	--	--	80	20	1030	630	.850	.0353	.0318	90.1
39.5	531	20	.155	0	--	--	59	41	980	622	.851	.0355	.0307	86.5
39.6	531	18	.161	0	--	--	42	58	800	587	.834	.0355	.0254	71.5
39.8	530	21	.155	2.6	--	--	100	--	1094	630	.854	.0344	.0316	91.9
39.6	529	20	.156	2.6	--	--	81	19	1058	625	.856	.0346	.0309	89.3
39.5	529	26	.156	2.7	--	--	59	41	1020	622	.858	.0353	.0307	87.0
39.6	530	19	.156	2.6	--	--	50	50	974	621	.852	.0354	.0303	85.6
39.5	530	21	.158	2.7	--	--	42	58	934	611	.852	.0352	.0291	82.7
44.5	534	19	.164	2.6	100	--	--	--	1230	645	.827	.0315	.0237	75.2
44.6	534	21	.156	2.6	100	--	--	--	1393	700	.850	.0361	.0303	83.9
46.3	527	23	.150	2.2	100	--	--	--	1595	760	.857	.0398	.0347	87.2
44.8	527	24	.149	2.5	100	--	--	--	1608	743	.860	.0411	.0357	86.9
44.5	538	25	.144	2.4	100	--	--	--	1750	777	.876	.0464	.0418	90.1
59.6	529	18	.165	2.5	100	--	--	--	1240	857	.829	.0297	.0231	77.8
59.8	528	20	.156	2.4	100	--	--	--	1420	938	.852	.0354	.0304	85.9
60.2	524	22	.152	2.5	100	--	--	--	1555	976	.859	.0377	.0337	89.4
59.6	530	25	.148	2.5	100	--	--	--	1678	1005	.866	.0408	.0374	91.7
59.5	533	23	.144	2.5	100	--	--	--	1745	1043	.879	.0455	.0424	93.2
59.5	529	24	.142	2.5	100	--	--	--	1843	1072	.888	.0492	.0461	93.7
59.9	525	22	.159	0	--	--	100	--	922	915	.847	.0297	.0280	94.3
59.5	536	22	.153	0	--	--	100	--	1017	957	.854	.0354	.0326	92.1
59.6	530	23	.151	0	--	--	100	--	1055	975	.860	.0381	.0342	89.8
59.4	531	24	.149	0	--	--	100	--	968	989	.862	.0404	.0361	89.4
59.0	540	25	.146	0	--	--	100	--	1165	1016	.870	.0459	.0401	87.4
59.2	536	25	.146	0	--	--	100	--	1247	1019	.872	.0461	.0398	86.3
60.0	524	23	.144	0	--	--	100	--	1405	1051	.881	.0503	.0424	84.3
79.8	531	18	.163	2.5	100	--	--	--	1243	1170	.834	.0302	.0246	81.5
80.1	535	21	.155	2.5	100	--	--	--	1405	1272	.856	.0352	.0315	89.5
80.5	530	25	.148	2.5	100	--	--	--	1643	1358	.867	.0400	.0377	94.3
80.6	532	24	.144	2.5	100	--	--	--	1735	1416	.879	.0448	.0427	95.3
81.1	527	25	.148	4.9	100	--	--	--	1718	1360	.865	.0398	.0371	93.2
78.3	535	21	.159	0	--	--	100	--	1002	1212	.855	.0308	.0292	94.8
78.7	535	21	.156	0	--	--	100	--	1352	1244	.854	.0333	.0311	93.4
78.4	535	22	.153	0	--	--	100	--	1025	1269	.859	.0362	.0336	92.8
77.9	535	26	.148	0	--	--	100	--	1162	1311	.866	.0416	.0373	89.7
78.9	530	25	.146	0	--	--	100	--	1352	1361	.875	.0462	.0404	87.4

TABLE I. - Concluded. PERFORMANCE DATA FOR EXPERIMENTAL COMBUSTOR IN A 48-INCH-DIAMETER RAM-JET ENGINE

(e) Combustor length, 78 inches; shroud length, 6 inches

Engine air flow, W_e, lb/sec	Inlet temperature, T_{in}, °F	Bypass air, W_b, percent	Combustor-inlet Mach number, M_{in}	Pilot fuel, percent stoichiometric	Main fuel distribution, percent, to profiles - A	B	C	D	Gas temperature near wall of exhaust nozzle, T_x, °F	Engine-outlet pressure, P_6, $\frac{lb}{sq\ ft\ abs}$	Pressure ratio across combustor, P_6/P_3	Fuel-air ratio: Actual, f/a_{act}	Fuel-air ratio: Ideal, f/a_{id}	Combustion efficiency, η_c, percent
59.8	537	18	0.168	- -	- -	- -	- -	- -	443	859	0.841	- - -	- - -	- -
59.3	532	19	.161	- -	- -	- -	- -	- -	443	913	.862	- - -	- - -	- -
59.5	530	19	.158	- -	- -	- -	- -	- -	430	954	.881	- - -	- - -	- -
59.6	527	21	.151	- -	- -	- -	- -	- -	422	1007	.889	- - -	- - -	- -
59.4	529	23	.147	- -	- -	- -	- -	- -	437	1048	.904	- - -	- - -	- -
39.6	535	18	.175	2.6	100	- -	- -	- -	885	510	.779	0.0249	0.0156	62.7
39.3	537	17	.165	2.6	100	- -	- -	- -	1098	569	.829	.0301	.0235	78.1
39.6	527	22	.154	2.6	100	- -	- -	- -	1200	623	.845	.0349	.0307	88.0
39.4	531	23	.148	2.6	100	- -	- -	- -	1353	664	.865	.0403	.0374	92.8
39.5	528	23	.143	2.6	100	- -	- -	- -	1490	692	.874	.0453	.0425	93.7
39.3	528	23	.141	2.6	100	- -	- -	- -	1497	714	.891	.0510	.0474	93.0
39.7	532	19	.168	2.6	- -	- -	100	- -	1086	553	.814	.0250	.0208	83.2
39.8	528	21	.159	2.6	- -	- -	100	- -	1270	601	.838	.0298	.0270	90.6
39.7	528	22	.152	2.5	- -	- -	100	- -	1324	634	.843	.0349	.0321	92.0
38.9	537	23	.152	2.7	- -	- -	100	- -	1353	624	.844	.0357	.0325	90.9
39.7	533	25	.148	2.6	- -	- -	100	- -	1489	659	.856	.0400	.0358	89.5
39.8	530	25	.147	2.6	- -	- -	100	- -	1488	662	.854	.0399	.0362	90.7
39.6	533	25	.146	2.6	- -	- -	100	- -	1674	681	.869	.0452	.0399	88.2
39.6	532	25	.143	2.6	- -	- -	100	- -	1813	699	.877	.0508	.0432	84.9
39.4	527	22	.152	2.7	- -	- -	90	10	1321	628	.843	.0351	.0319	90.9
39.3	528	23	.152	2.7	- -	- -	80	20	1292	628	.844	.0353	.0320	90.7
39.0	540	21	.154	2.7	- -	- -	69	31	1282	621	.846	.0355	.0315	88.7
39.2	538	22	.154	2.6	- -	- -	59	41	1230	622	.846	.0353	.0312	88.4
39.3	530	22	.154	2.7	- -	- -	50	50	1192	622	.847	.0354	.0311	87.9
39.2	529	21	.155	2.5	- -	- -	41	59	1114	615	.848	.0353	.0303	85.8
39.1	532	22	.157	2.6	- -	- -	30	70	1088	606	.845	.0353	.0292	82.7
39.6	531	24	.147	2.6	- -	- -	90	10	1459	660	.854	.0400	.0363	90.8
39.6	533	25	.148	2.6	- -	- -	80	20	1408	661	.857	.0401	.0363	90.5
39.6	533	25	.147	2.6	- -	- -	69	31	1388	661	.854	.0400	.0365	91.3
39.6	535	26	.147	2.6	- -	- -	59	41	1368	660	.852	.0401	.0362	90.3
59.6	530	19	.172	2.2	100	- -	- -	- -	1047	799	.801	.0248	.0183	73.9
59.6	529	20	.162	2.2	100	- -	- -	- -	1237	874	.830	.0295	.0247	83.7
59.7	526	23	.152	2.2	100	- -	- -	- -	1313	958	.852	.0353	.0325	92.1
59.5	529	25	.146	2.2	100	- -	- -	- -	1465	1016	.870	.0403	.0389	96.5
59.4	528	24	.143	2.2	100	- -	- -	- -	1583	1057	.885	.0456	.0450	98.7
60.1	525	19	.166	2.3	- -	- -	100	- -	1176	851	.821	.0246	.0222	90.0
59.6	531	21	.157	2.3	- -	- -	100	- -	1368	914	.841	.0296	.0284	95.9
59.8	534	22	.153	2.3	- -	- -	100	- -	1363	960	.852	.0349	.0325	93.0
59.6	528	24	.148	2.3	- -	- -	100	- -	1521	996	.859	.0402	.0368	91.5
59.7	531	24	.142	2.3	- -	- -	100	- -	1694	1024	.846	.0452	.0397	87.8
80.1	530	17	.172	2.3	100	- -	- -	- -	1068	1090	.810	.0250	.0192	76.8
79.9	533	20	.160	2.4	100	- -	- -	- -	1273	1201	.838	.0303	.0266	87.8
80.7	526	23	.153	1.8	100	- -	- -	- -	1318	1289	.853	.0345	.0323	93.6
79.6	532	23	.152	2.4	100	- -	- -	- -	1338	1289	.856	.0353	.0335	94.9
80.1	527	25	.146	2.4	100	- -	- -	- -	1562	1369	.870	.0404	.0392	97.0
80.1	527	23	.142	2.3	100	- -	- -	- -	1668	1426	.883	.0451	.0447	99.1
80.2	527	18	.166	2.4	- -	- -	100	- -	1234	1146	.827	.0250	.0228	91.2
80.2	529	21	.158	2.4	- -	- -	100	- -	1401	1230	.847	.0299	.0287	96.0
80.2	531	22	.152	2.4	- -	- -	100	- -	1410	1289	.853	.0353	.0329	93.1
80.3	528	25	.148	2.4	- -	- -	100	- -	1593	1343	.863	.0402	.0368	91.5
80.3	528	25	.145	2.4	- -	- -	100	- -	1748	1383	.869	.0452	.0405	89.6

TABLE II. - IGNITION TESTS WITH EXPERIMENTAL COMBUSTOR IN 48-INCH-DIAMETER RAM-JET ENGINE

Nominal values of flow parameters immediately before tests.

Engine air flow, W_e, lb/sec	Inlet tempera-ture, T_{in}, °F	Pilot fuel, percent stoichio-metric	Main fuel distribution profile	Engine outlet pressure, P_6, $\frac{lb}{sq\ ft\ abs}$	Pilot pressure, P_p, $\frac{lb}{sq\ ft\ abs}$	Fuel-air ratio, f/a_{act}	Result: Start	Result: No start
40	530	0	A	340	260	0.033	x	
40	530	0	C	340	260	.035	x	
40	530	2.5	A	340	260	.035		x
40	530	2.5	A	340	260	.035	x	
40	530	2.5	C	340	260	.035	x	
40	530	2.5	C	340	260	.035	x	
40	530	2.5	0.5 C, 0.5 D	340	260	.035	x	
40	530	2.5	0.5 C, 0.5 D	340	260	.045	x	
45	530	0	A	390	300	.033	x	
45	530	2.5	A	390	300	.035	x	
45	530	2.5	A	390	300	.035		x
50	530	0	A	430	330	.035	x	
50	530	2.5	A	430	330	.035	x	
50	530	2.5	A	430	330	.035	x	
60	530	0	C	520	400	.035	x	
60	530	(0 - 2.5)	none	520	400	- - -	x	
60	530	2.5	none	520	400	- - -	x	
60	530	2.5	A	520	400	.035	x	
60	530	2.5	A	520	400	.035	x	
60	530	2.5	A	520	400	.035	x	
60	530	2.5	A	520	400	.035	x	
60	530	2.5	A	520	400	.035	x	
60	530	2.5	C	520	400	.035	x	
80	400	2.5	A	640	490	.035	x	
110	400	2.5	none	880	670	- - -	x	
110	400	2.5	A	880	670	.035	x	
110	400	2.5	A	880	670	.035	x	
110	400	2.5	A	880	670	.035	x	

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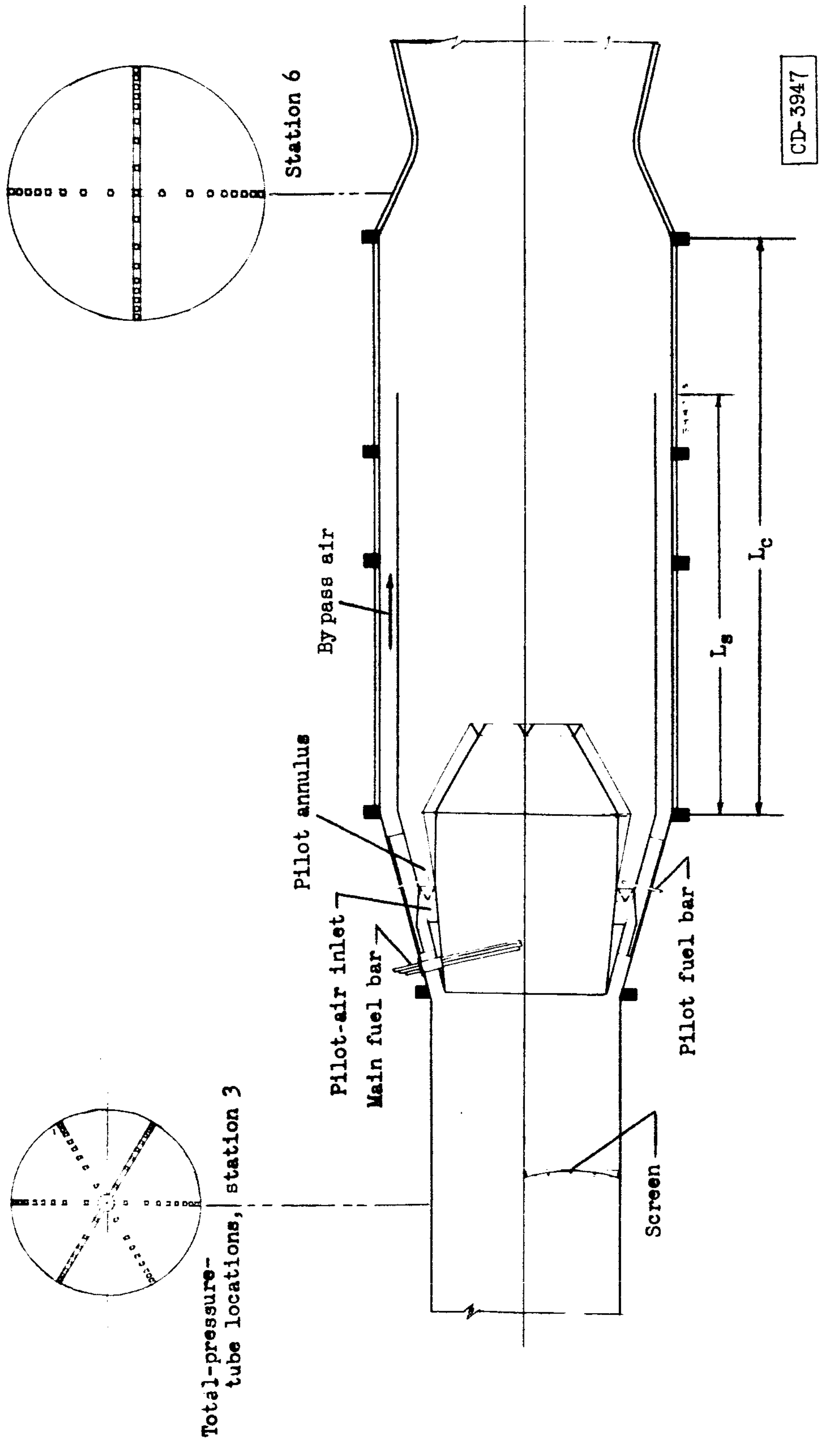

Figure 1. - Sketch of combustor configuration.

3576

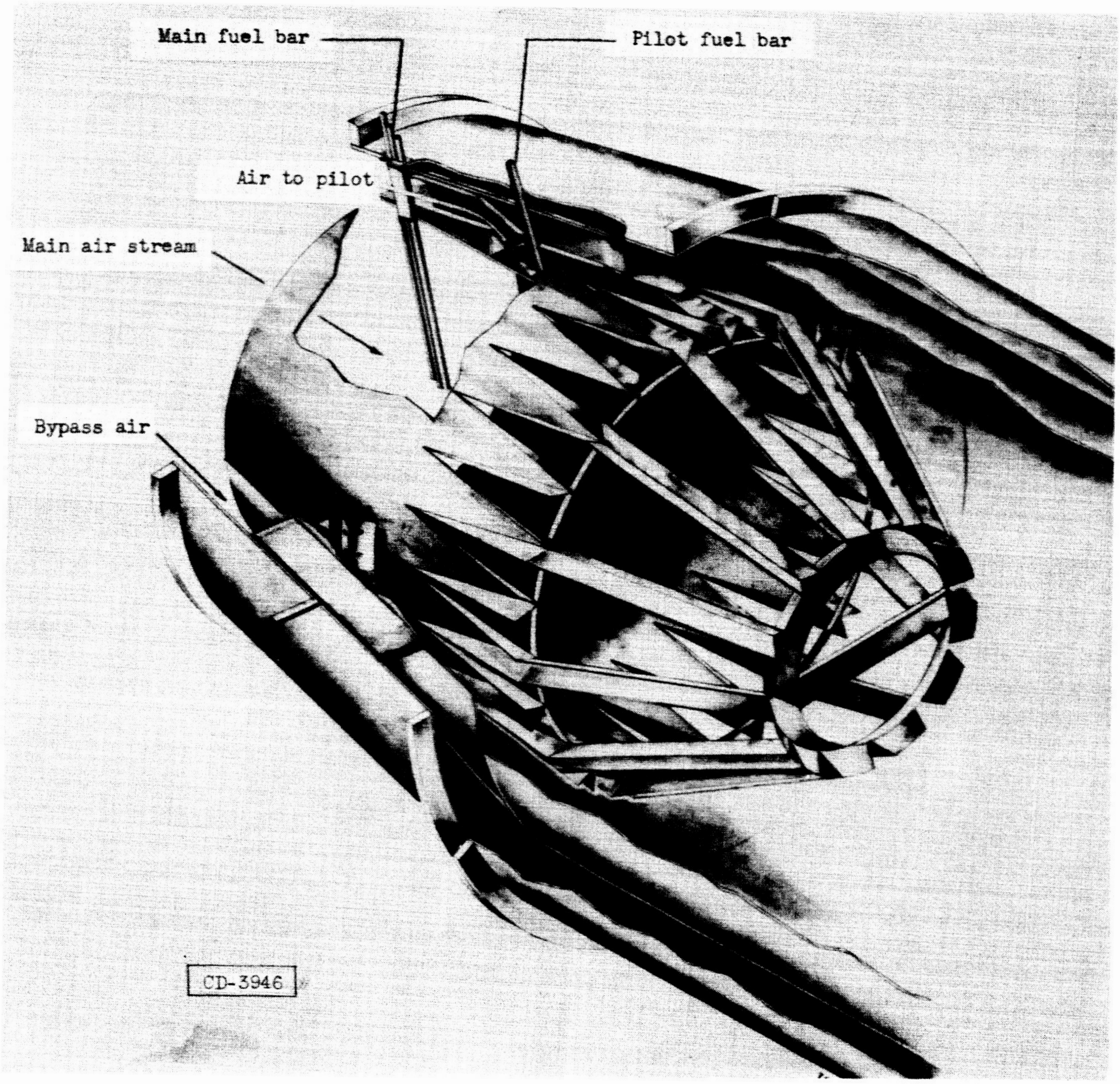

Figure 2. Cutaway view of combustor.

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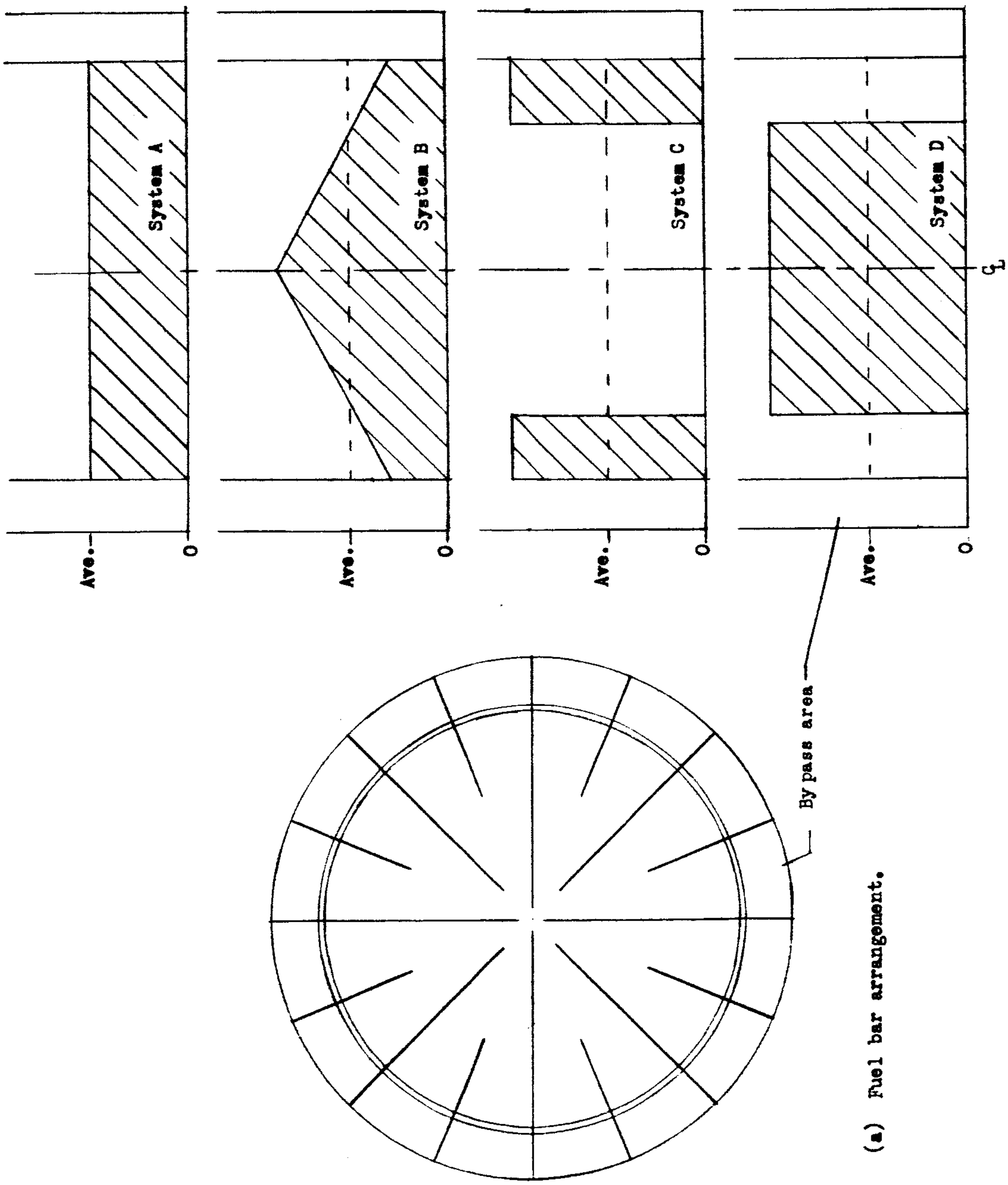


(a) Fuel bar arrangement.

(b) Fuel profiles used.

Figure 3. - Fuel-injection systems.

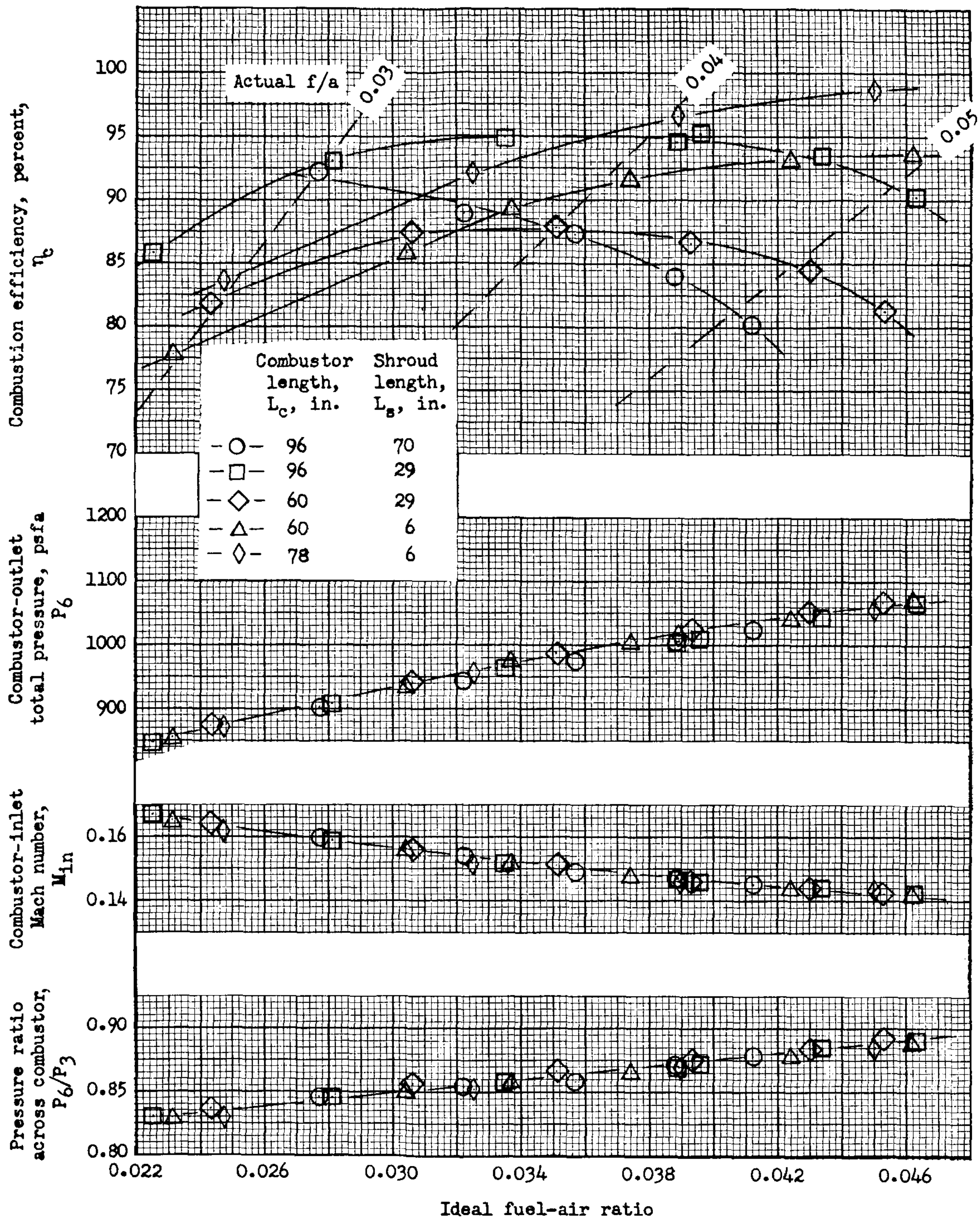


Figure 4. Performance of experimental combustor. Air flow, 60 pounds per second; air temperature, 530°F; fuel profile 'A'.

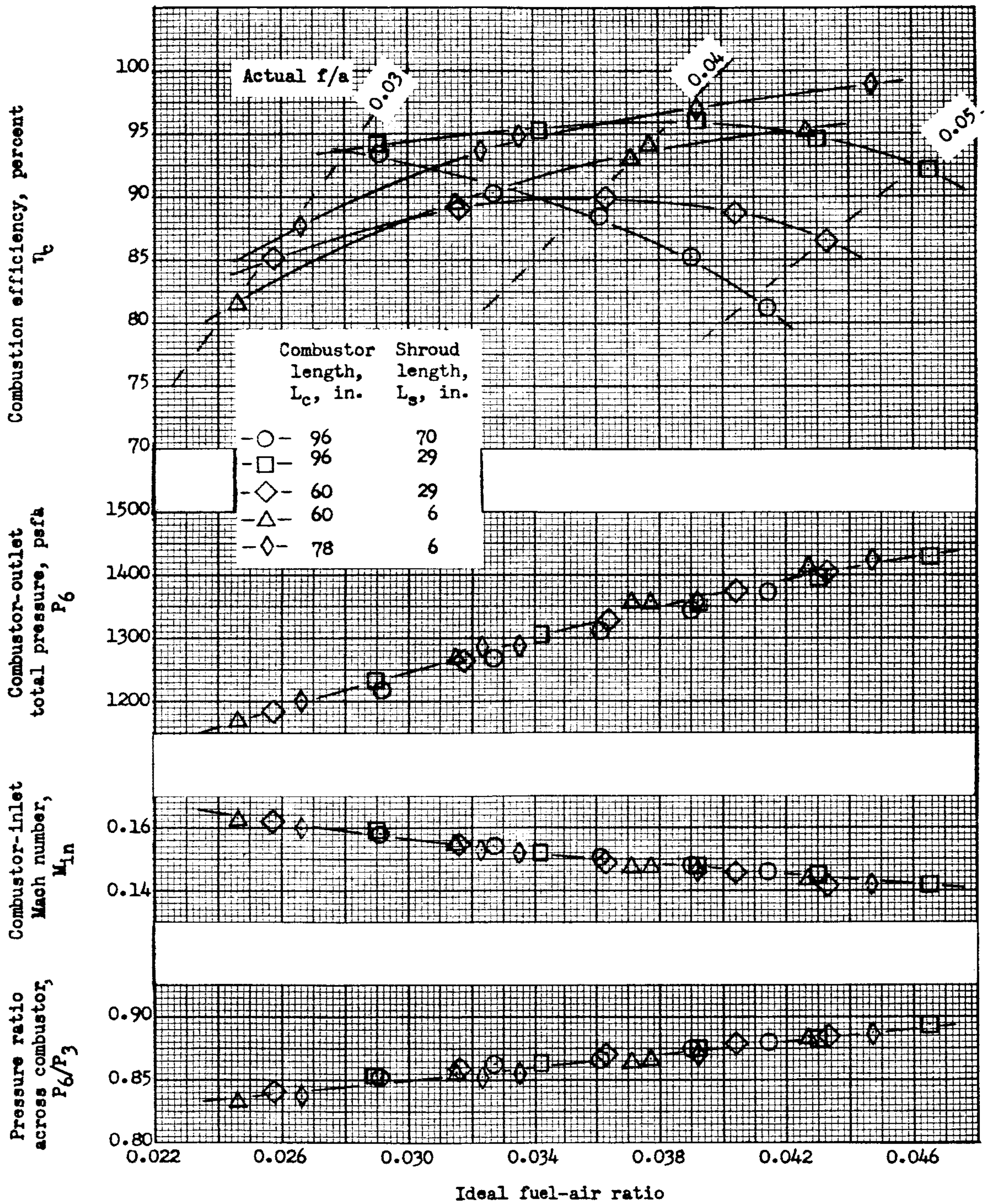


Figure 5. Performance of experimental combustor. Air flow, 80 pounds per second; air temperature, 530°F; fuel profile 'A'.

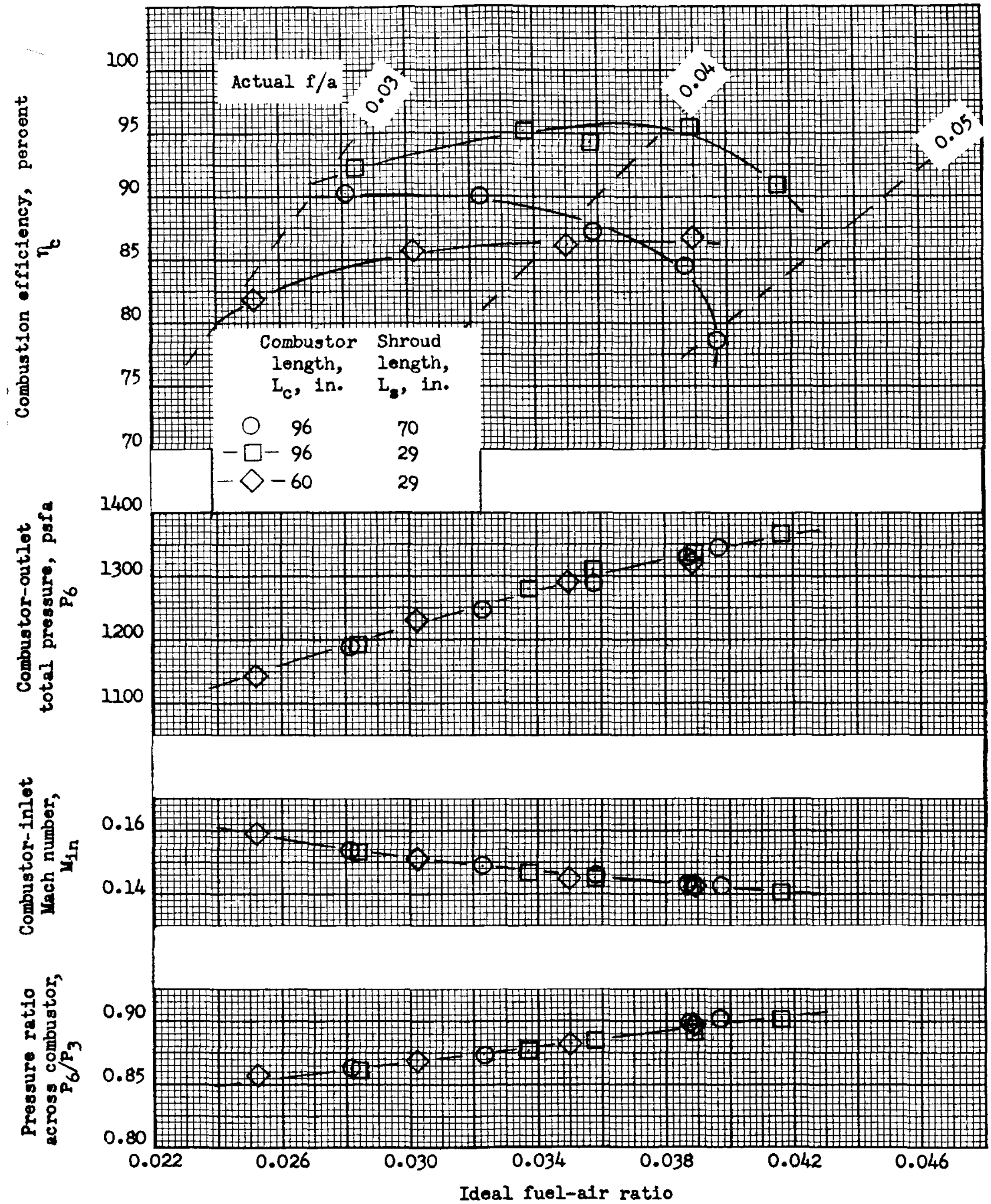


Figure 6. Performance of experimental combustor. Air flow, 80 pounds per second; air temperature, 400°F; fuel profile 'A'.

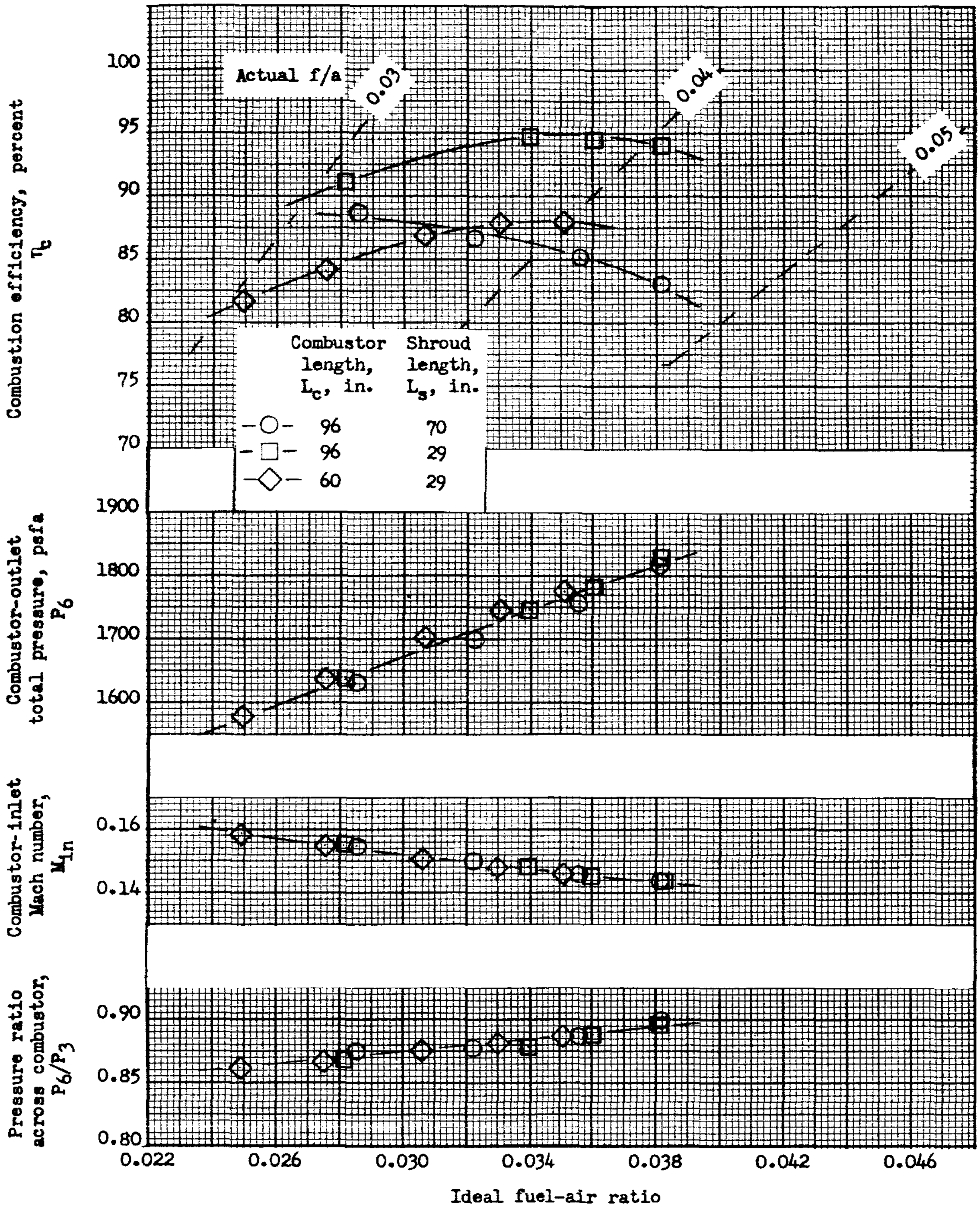


Figure 7. Performance of experimental combustor. Air flow, 110 pounds per second; air temperature, 400°F; fuel profile 'A'.

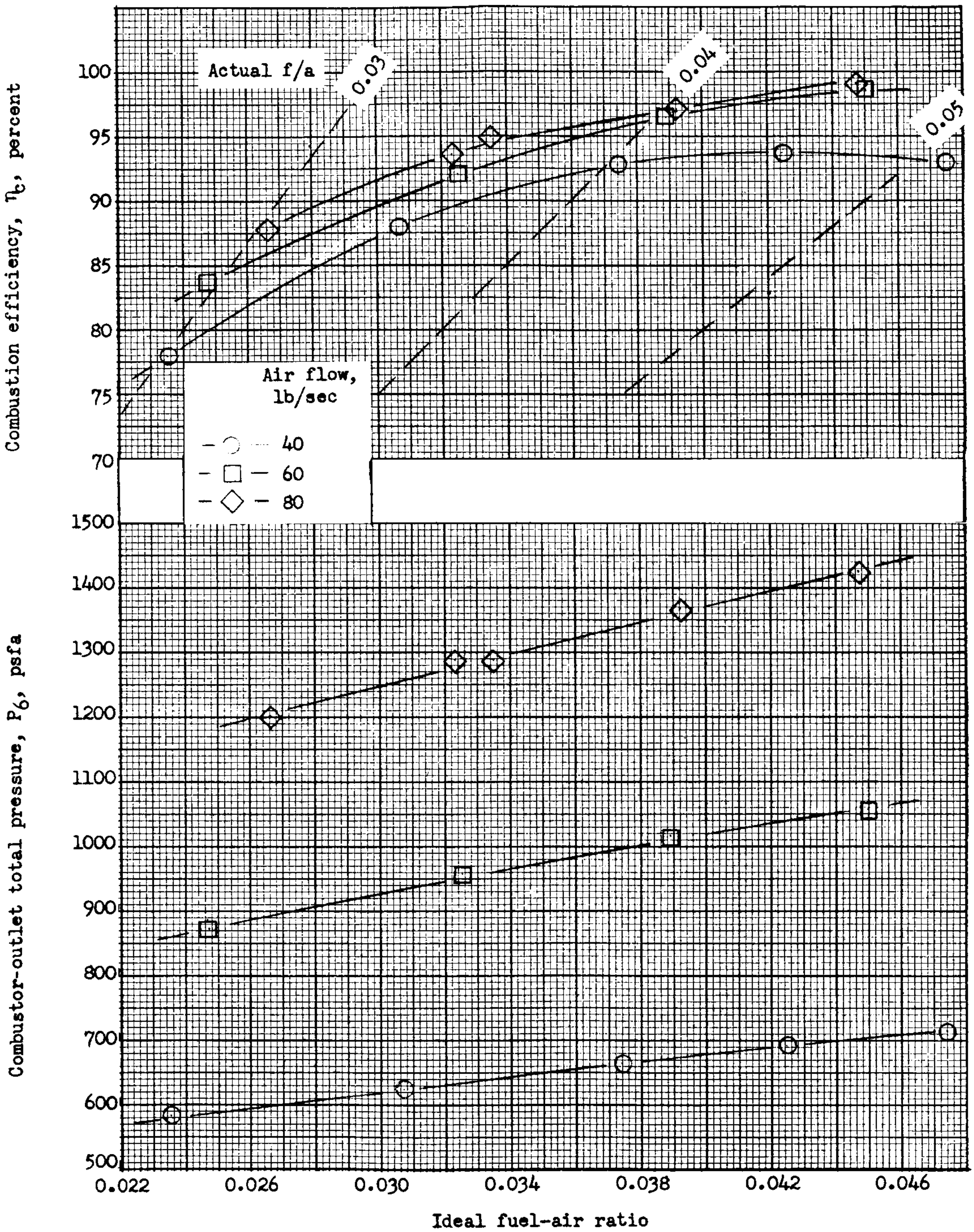
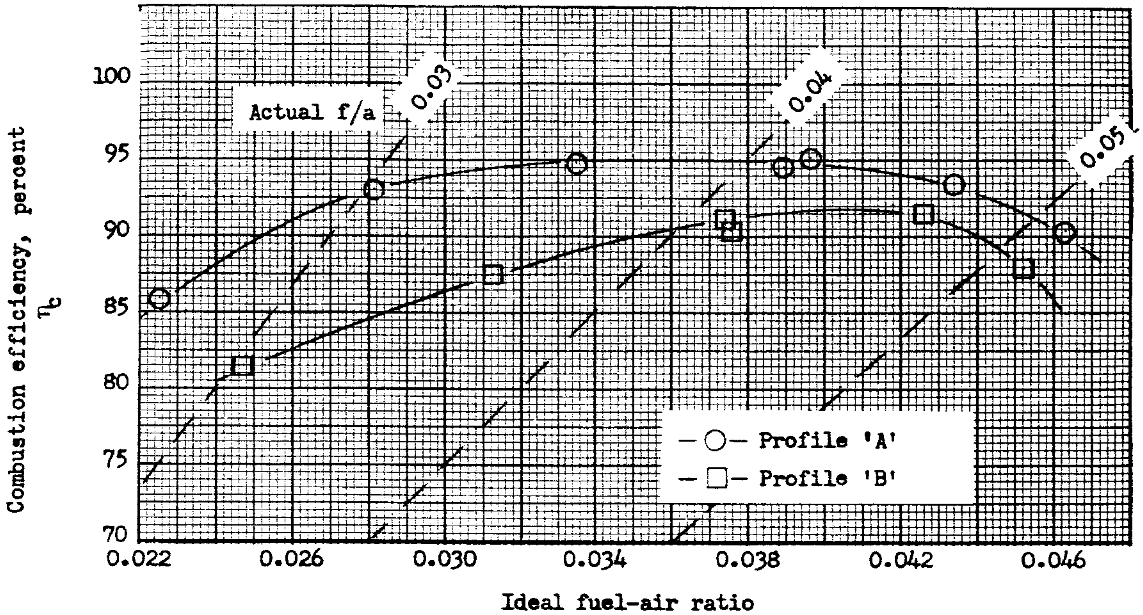
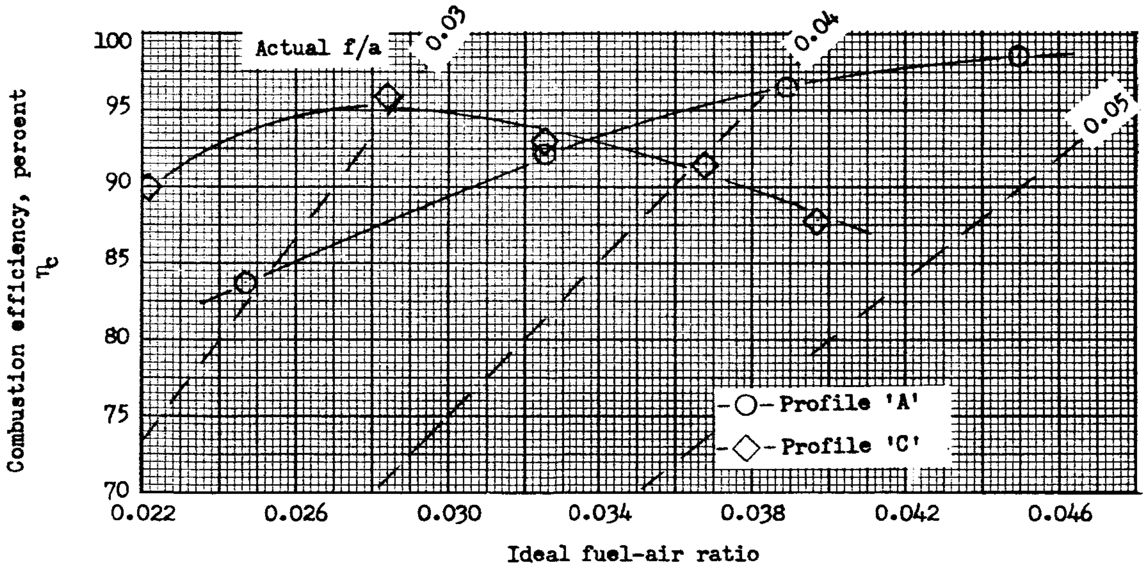


Figure 8. Performance of experimental combustor at three pressure levels. Combustor length, 78 inches; shroud length, 6 inches; fuel profile 'A'.

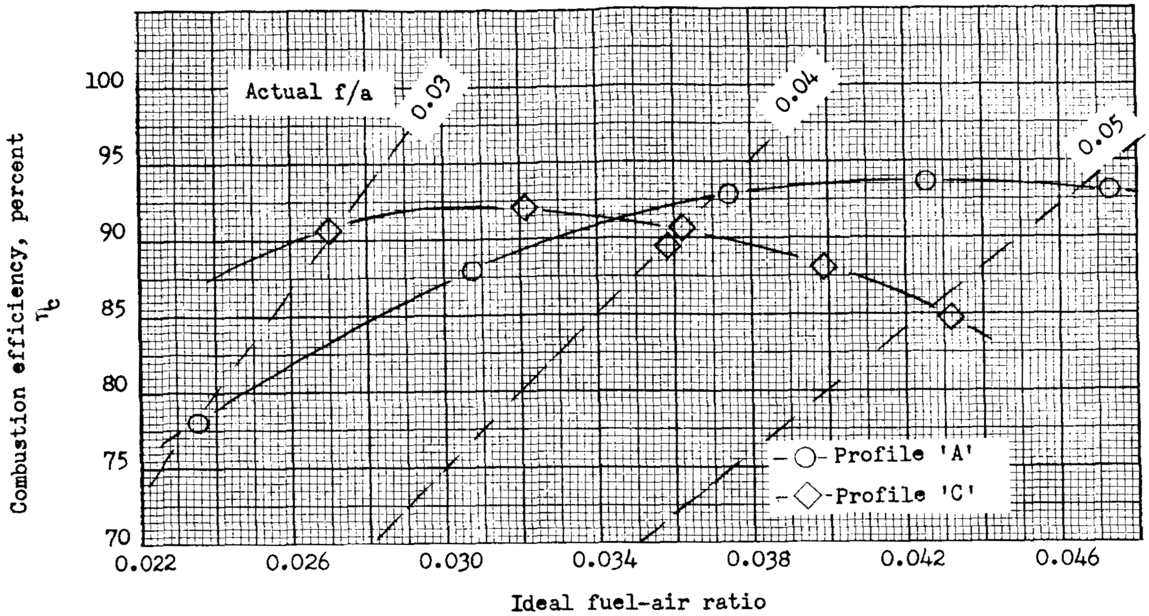


(a) Fuel profiles 'A' and 'B'. Combustor length, 96 inches; shroud length, 29 inches; air flow, 60 pounds per second; air temperature, 530°F.

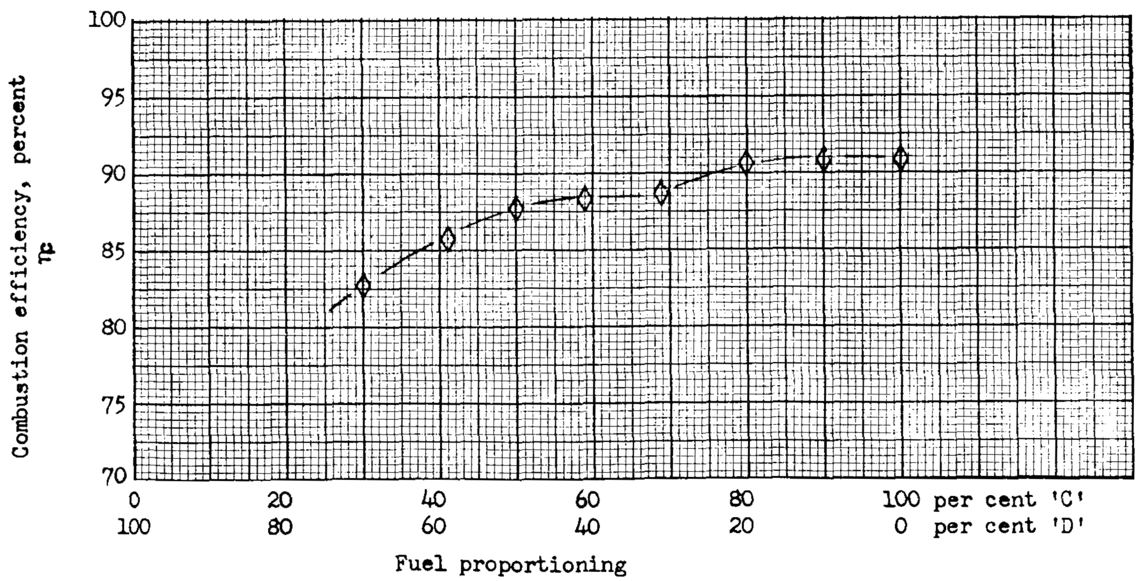


(b) Fuel profiles 'A' and 'C'. Combustor length, 78 inches; shroud length, 6 inches; air flow, 60 pounds per second; air temperature, 530°F.

Figure 9. Performance of experimental combustor with varying fuel profiles.



(c) Fuel profiles 'A' and 'C'. Combustor length, 78 inches; shroud length, 6 inches; air flow, 40 pounds per second; air temperature, 530°F.



(d) Fuel proportioned between profiles 'C' and 'D'. Combustor length, 78 inches; shroud length, 6 inches; air flow, 40 pounds per second; actual fuel-air ratio, 0.035; air temperature, 530°F.

Figure 9. - Concluded. Performance of experimental combustor with varying fuel profiles.

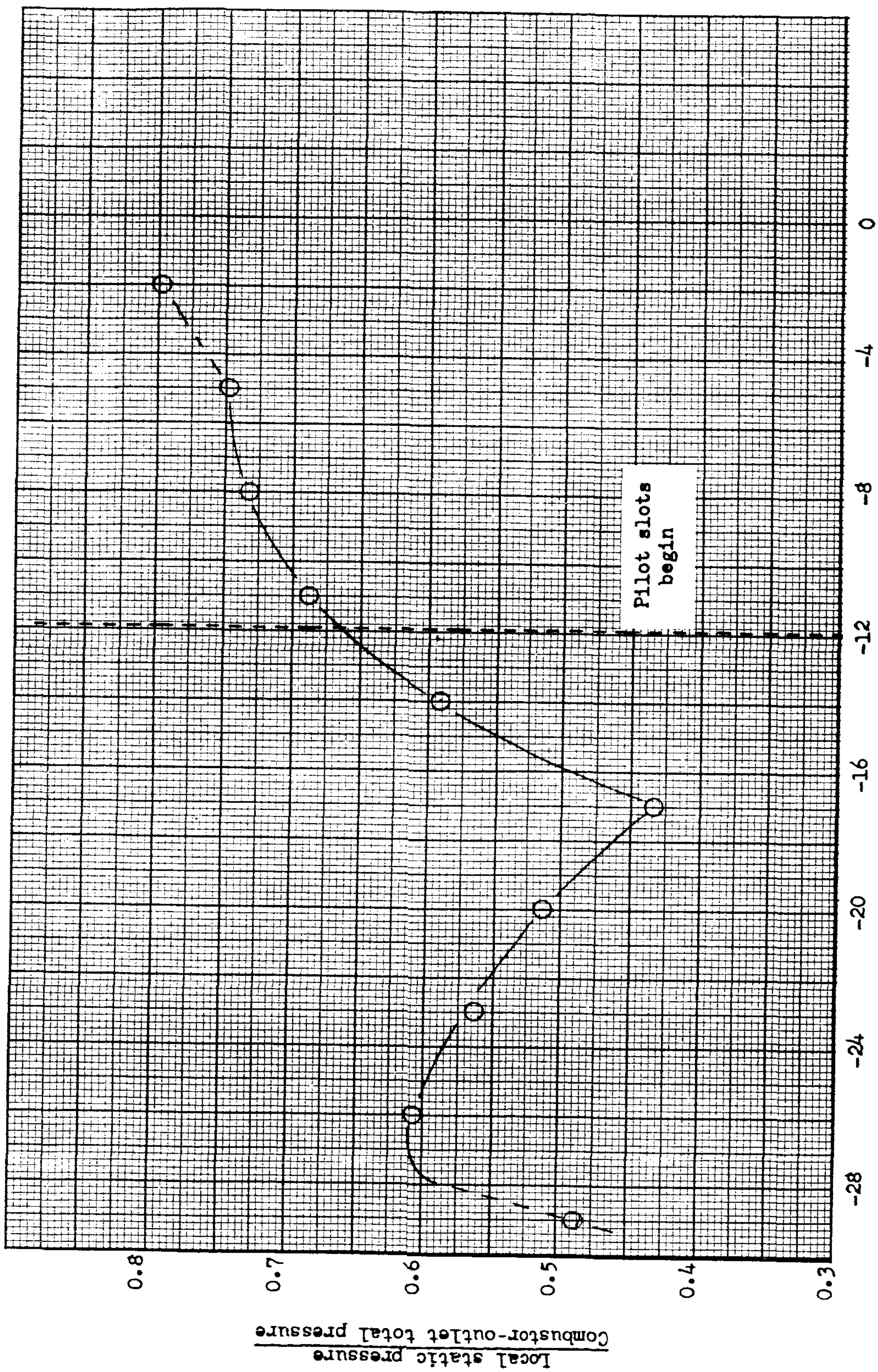


Figure 10. Axial distribution of pressure along inside surface of experimental combustor with isothermal flow. Combustor length, 78 inches; shroud length, 6 inches; air flow, 80 pounds per second; air temperature, 530°F.

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